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The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives

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ABSTRACT

Increasing oil palm plantations, both for obtaining crude palm oil (CPO) and for the production of biobased products, have generated growing concern about the impact of greenhouse gas (GHG) emissions on the environment. Colombia has the potential to produce sustainable biobased products from oil palm. Nevertheless, national GHG emissions have not yet been reported by this sector. Achieving the collection of the total primary data from the oil palm sector, in Colombia, entails a tremendous challenge. Notwithstanding, for this study, the data collection of 70% of the production of fresh fruit bunches (FFB) was achieved. Therefore, *current situation* of CPO production in Colombia is analyzed, including 1) GHG emissions calculation, 2) net energy ratio (NER), and 3) economic performance. Moreover, the analysis includes two future scenarios, where the CPO production chain is optimized to reduce GHG emissions. *Future scenario A* produces biodiesel (BD), biogas, cogeneration, and compost; while *future scenario B* produces BD, biogas, cogeneration, and pellets. The methodology, for all the scenarios, includes life-cycle assessment and economic analysis evaluation. The results show a significant potential for improving the current palm oil production, including a 55% reduction in GHG emissions. The impact of land-use change must be mitigated to reduce GHG emissions. Therefore, a sustainable oil palm expansion should be in areas with low carbon stock or areas suitable/available to the crop (e.g., cropland, pastureland). Avoiding the deforestation of natural forests is required. Besides, crop yield should be increased to minimize the land use, using biomass to produce biobased products, and capture biogas to reduce methane emissions. In the biodiesel production life-cycle, the NER analysis shows the fossil energy consumed is lower than the renewable energy produced. Regarding the economic performance, it shows that in an optimized production chain, the capital expenditure and operational expenditure will decrease by approximately 20%.

1. Introduction

Palm oil is considered an economic driver (Thomas et al., 2015) due to its versatility, high productivity (around 3.4 tons (t) crude palm oil (CPO) per hectare (ha)) (EPOA, 2016) (Fry, 2017) (Fedepalma, 2017a), and its lower production cost in comparison to other vegetable oils (Khasanah et al., 2015). Indonesia (10,830 thousand ha) and Malaysia (5,150 thousand ha) are the countries with the largest production with around 78% of the global production area, while Colombia (465 thousand ha) is the fifth-largest oil palm producing country with a 2.3% share of global production area (Fedepalma, 2018a). Given that, currently, the demand for food and bio-based products puts pressure on greater agricultural production, the oil palm sector becomes a key player to help meet some of these demands (Mesa, 2017). Notwithstanding, oil palm cultivation has generated controversy because of the deforestation caused in tropical forests of some producing countries (Ramdani and Hino, 2013) (Khasanah, 2019). The debate focuses on the environmental risks associated with deforestation such as the loss of biodiversity, soil quality, water supply, landscape, land-use change (LUC) and release of greenhouse gases (GHG) emissions mainly by the removal of carbon stock from the soil (Thomas et al., 2015) (Khatun et al., 2017). In addition, the

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Abbreviations

bbl	Barrels of oil
BD	Biodiesel
BioPB	Name of a model developed by Cenipalma-Colombia
C	Carbon
CAPEX	Capital expenditure
CH_4	Gas methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
COD	Chemical oxygen demand
COP	Colombian pesos
CPO	Crude palm oil
EFB	Empty fruit bunches
FFA	Free fatty acid
FFB	Fresh fruit bunches
GHG	Greenhouse gases
h	Hour
ha	Hectares
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (Institute of Hydrology, Meteorology and Environmental Studies of Colombia)
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
ISO	International Organization for Standardization
kg	Kilograms
kW	Kilowatts
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Low heating value
LUC	Land use change
m^3	Cubic meter
Mha	Million hectares
MJ	Megajoules
NPV	Net present value
NER	Net energy ratio
OPEX	Operational expenditure
POM	Palm oil mill
POME	Palm oil mill effluent
Ppm	Parts per million, which also means milligrams per liter
SBE	Spent bleaching earth during the palm oil refining process
T	Tons
UPRA	Unidad de Planeación Rural Agropecuaria (Rural Agricultural Planning Unit)
USD	United States dollars

accounting system for GHG emissions, especially bioenergy, has been questioned because it is considered to be carbon-neutral. But to justify the potential to reduce emissions, an analysis of the bioenergy must include the biomass source, the effects on land use, the production process and the emissions from its final use (Searchinger et al., 2009). Then, GHG emissions from bioenergy are representative only when biomass growth and collection capture carbon above the level of what would be sequestered (Searchinger et al., 2009). Therefore a strong relationship between the GHG emissions and the LUC should be considered, since, the LUC that occurs in areas that initially had a carbon stock greater than areas with oil palm plantations, causes a debt of carbon from the aboveground. While establishing oil palm plantations in areas that previously had shrubs or grasslands, debt-free can be obtained (Khasanah et al., 2015). Although oil palm expansion has been associated with deforestation in the lead producing countries (Khasanah, 2019) a different situation has been reported for Colombia, where the oil palm expansion has been associated mainly with the conversion of scrublands, croplands, and savannas (Henson et al., 2012) (Castiblanco et al., 2013) (Castanheira et al., 2014) (Furumo and Aide, 2017).

Several studies have reported the GHG emissions of palm oil production (Kusin et al., 2017). However, those studies have used a variety of assumptions, system boundaries, and functional units to calculate and report the emissions. Taking into account that the emissions of the agricultural sector should be harmonized around the flow of the main product traded (Durlinger et al., 2017), the emissions of the palm oil sector should be reported in tons of CPO. Such is the case in a study regarding two CPO production systems that were analyzed for Malaysia and Indonesia, but emissions were expressed in tons of fresh fruit bunches (FFB) instead of reporting them in tons of CPO (Stichnothe and Schuchardt, 2011). Regarding a study in Thailand however, only the stage of oil palm cultivation was evaluated thus the results were expressed in FFB as the main product marketed (Silalertruksa et al., 2017). Studies have reported the GHG emissions in CPO production for Malaysia and Indonesia (Wicke et al., 2008) (Stichnothe and Schuchardt, 2011) (Lam et al., 2019) have been higher than the emissions reported in studies regarding Colombia (Yáñez et al., 2011) (Henson et al., 2012) (Castanheira et al., 2014) (Garcia-Nunez et al., 2016) (Rivera-Méndez et al., 2017). For instance, a study in Indonesia reported a GHG footprint for the CPO production in a range between 0.7 and 26 t CO_2eq t^{-1} CPO (Lam et al., 2019), while for Colombia a study showed a range between -3.0 and 5.3 t CO_2eq t^{-1} CPO (Castanheira et al., 2014). Nevertheless, there is a consensus on the potential for emission reduction in the oil palm sector worldwide as long as good agro-industrial practices are used. It is based on non-deforestation, landscape and soil management, non-use of high carbon stock land, increase in sustainable yield, and the use of biomass in biobased products (Khasanah et al., 2015) (Garcia-Nunez et al., 2016) (Afriyanti et al., 2016) (Abdul-manan, 2017) (RSPO, 2017) (Woittiez, 2019) (Lam et al., 2019).

Colombia has the potential for sustainable oil palm expansion with zero deforestation to go from 0.5 million hectares (Mha) (Fedepalma, 2018b) to 23 Mha (UPRA, 2018). However, strong guidelines, policies, and criteria are required to promote and regulate natural resources and efficient land use suitable for oil palm crops (Castanheira et al., 2014) (Woittiez, 2019) (Khasanah, 2019). As a result, the national government is working on the zoning of the agricultural and forestry sector to identify the geographical areas suitable for planting and livestock production (UPRA, 2019). It is emphasized that the use of those areas is conditioned to the environmental, socioeconomic and management characteristics of each area and each productive chain (UPRA, 2016). In the Colombian oil palm sector, there is a growing awareness of the environmental and social concerns (Espinosa, 2016) so much so, that the sector has adopted various agreements to improve the sustainability of CPO production (MADS, 2017a). This is in line with the shift to a low-carbon development model in the country to reduce GHG emissions, increase the protected areas, promote sustainable development, and avoid deforestation (Garcia Arbelaez et al., 2016) (MADS, 2017b) (WWF-Colombia, 2017). Although in Colombia, several studies have been done to identify the GHG emission of palm oil production, those are based on a limited number of mills or plantations, but it does not involve the whole production chain of the country. Thus, the primary objective of this study is to evaluate the CPO production chain in Colombia for the *current situation* and for two *future scenarios*. The analysis includes 1) GHG emissions calculation, 2) net energy ratio, and 2) economic performance (net present value, internal rate of return, capital expenditure, and operational expenditure). The assessment of the future scenarios includes the production of biodiesel (BD), cogeneration, compost/pellets, and biogas capture. This document is structured as follows: Section 1 describes the present introduction. Section 2 describes the methodology, scenarios, and data sources. Section 3 shows the results of the mass and energy balance, GHG balance to the national and regional level, and the economic performance. Section 4 offers a discussion, and finally, Section 5 outlines the conclusions.

2. Methodology

This study analyzed the GHG emissions and economic performance of the Colombian palm oil sector for the current situation (2017) and for two future scenarios. Moreover, the energy balance of the production chain is evaluated through the indicator Net energy ratio (NER). For the economic performance, the indicators evaluated are the net present value (NPV), internal rate of return (IRR), capital expenditure (CAPEX), and operational expenditure (OPEX). Fig. 1 shows a flowchart with an overview of the methodology and the type of results obtained.

Scenarios:

- ***Current situation.*** This scenario corresponds to the current status of the palm oil production chain in Colombia (2017), which includes oil palm cultivation, transportation of FFB, and palm oil mills (POMs). Emissions are analyzed at the national and regional scales.
- ***Future scenarios.*** A future optimized CPO production is analyzed to minimize GHG emissions and reduce production costs. The future scenarios include cogeneration (see Fig. 13 of Annex A.2), compost production, and pellet production (see Garcia-Nunez et al., 2016 to identify other biomass uses). Also, the biogas capture to use as renewable energy is mandatory. Biodiesel production is included since Colombian legislation allows the use of biofuels in the fossil fuel supply matrix for land transport (UPME, 2009). The two future scenarios are described below.
  - ***Future scenario A.*** The improvements proposed are influenced by an increase in yield, a reduction in the use of chemical fertilizers, LUC mitigation, and value-added biomass production. To mitigate LUC emissions, oil palm must be planted on land with a lower carbon stock such as marginal lands or conventional agricultural land (Wicke et al., 2012) (Castiblanco et al., 2013). However, when it occurs on agricultural lands, it may produce the displacement of the production of food and feed elsewhere (Gerssen-Gondelach, 2015). Therefore, it is essential that land use be complemented by high crops yield to mitigate the LUC in terms of GHG emissions (Wicke et al., 2012). This scenario includes the analysis of oil palm plantation, FFB transportation, POM, BD plant, cogeneration, and the use of the empty fruit bunches (EFB) in **compost** production.
  - ***Future scenario B.*** This scenario includes all the conditions mentioned in *future scenario A*; however, in *scenario B*, the EFBs are used to produce **pellets** instead of compost.

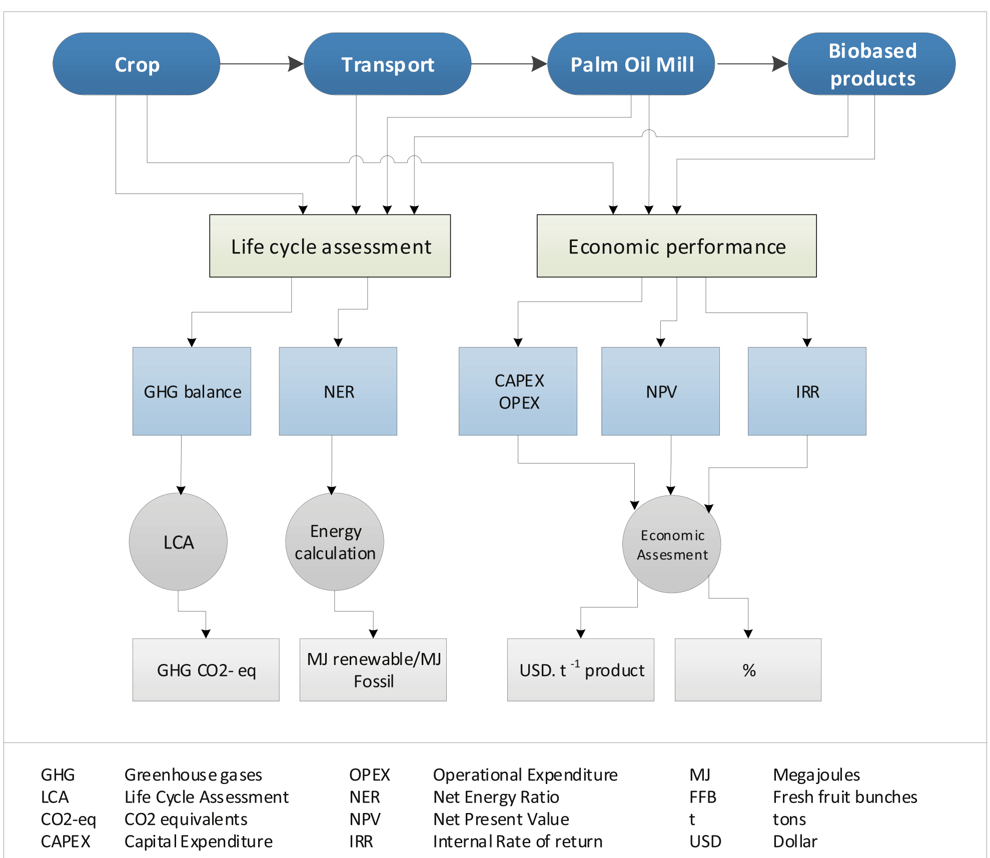


Fig. 1. Flowchart of the methodology developed in this study, which shows the stages of the BD chain analyzed per indicator, the indicators evaluated, the method used, and the expected outcomes. Biobased products include BD, biogas, compost, pellets and cogeneration (based on van der Hilst, 2012).

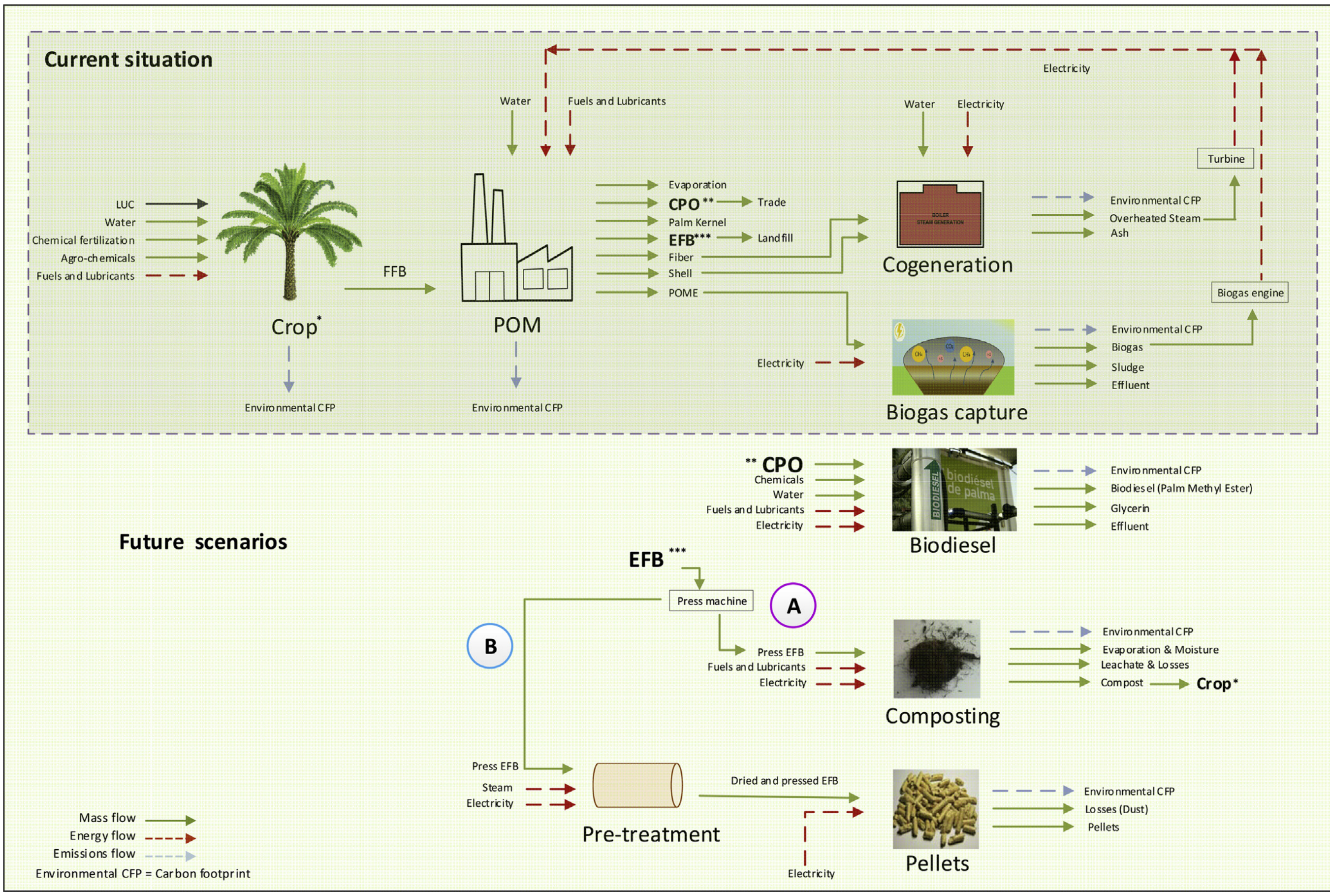


Fig. 2. System boundaries for current situation, future scenario A (compost production), and future scenario B (pellet production).

2.1. GHG emissions

GHG emission reduction is an important driver of sustainable biobased products; therefore, this indicator is analyzed to evaluate the *current situation* and the future scenarios of the Colombian palm oil sector. Fig. 2 shows the system boundaries for each scenario. A detailed life cycle inventory (LCI) is performed using the BioPB[1] model for the CPO production until the mill, while an excel spreadsheet was used to multiply LCI inputs with the corresponding emission factor for the biodiesel production (i.e., physical refining, transesterification, esterification of the free fatty acid (FFA), BD purification, glycerin purification, and methanol recovery). The functional unit 1 t CPO is used since the CPO is considered as the main product of the current oil palm chain in Colombia. The emissions[2] were calculated using the Life cycle assessment (LCA) methodology (ISO 14067), Intergovernmental Panel on Climate Change (IPCC) guidelines,[3] and databases from Ecoinvent and the software SimaPro 8.5. To analyze the impact of LUC on the GHG emissions in the *current situation*, a sensitivity analysis of carbon-stock values from land converted to oil palm was undertaken (see sections 2.4.1).

2.2. Net energy ratio

The net energy ratio (NER) is an indicator of the life cycle energy balance of a product, which is expressed as the ratio between the renewable energy produced (outputs) and the fossil energy consumed (inputs) (Yáñez Angarita et al., 2009) (Garcia-Nunez et al., 2016). The NER was selected to compare the scenarios. In the *current situation*, the sum of the fossil energy inputs includes the diesel used in cultivation, FFB transportation, and the POM. The sum of renewable energy outputs includes CPO and surplus electricity. In *future scenario A*, fossil energy input includes the diesel used in cultivation, FFB transportation, POM, compost production, and the BD plant. In *future scenario B*, fossil energy input includes the diesel used in cultivation, FFB transportation, POM, BD plant, and pellets production.

2.3. Economic performance

To evaluate the economic performance of the palm oil chain, the indicators NPV, IRR, CAPEX, and OPEX are calculated for all the scenarios. The oil palm plantation is assumed to have a lifespan of 30 years. The data collected during the fieldwork (see section 2.4) and previous studies (Mosquera et al., 2018) were used for the calculations. It is assumed that the CAPEX investment is made in the first year (acquisition costs, purchase of property, machinery,

[1] BioPB is a model developed by Cenipalma, which contains a database of the Colombian palm oil production chain and its biobased products. This model allows for the calculation of the mass and energy flows within the system boundaries for CPO production of each scenario.

[2] The greenhouse gases analyzed in the CPO production chain were CH_4 produced during the organic degradation of palm oil mill effluent (POME); CO_2 produced along the CPO production chain, and N_2O generated from the managed soil and chemical fertilization of palm cultivation.

[3] IPCC equations used: equation 2.1 to calculate annual carbon stock changes; equation 2.5 for LUC emissions; equations 11.1; 11.9 and 11.10 for N_2O emissions.

and equipment, etc.). The OPEX includes all activities related to FFB production (crop), CPO (mill), and BD plant. The NPV[4] and IRR are used to determine the profitability of the business.

2.4. Data sources

The data[5] for this study was collected during field visits to 28 POMs in three Colombian oil palm regions, which accounted for 70% of the FFB processed in 2017 in Colombia. Although in Colombia, there are four oil palm regions, this study is focused on three of them which including the central region (10 mills), eastern region (10 mills), and northern region (8 mills). The southwestern region was not included in this study, as palm oil production was much lower than in the other regions. The data on the production and management of the plantations was obtained from 11 plantations that belong to the owners of certain of the 28 surveyed POMs.

2.4.1. Emissions data in the current situation

In the *current situation*, the emissions were calculated individually for each of the 28 POMs. To analyze the regional and national emissions, the average emissions from the 28 mills was calculated. The GHG emissions calculations for each scenario are further explained in the following subsections. In addition, to analyze the impact of LUC on the GHG emissions in the *current situation*, an assessment of the carbon stock values from land converted to oil palm was undertaken.

2.4.1.1. LUC in the current situation. Table 1 shows the percentage of areas converted to oil palm at the regional and national scales. The regional scale focuses on an analysis of the three oil palm regions in Colombia, which differ in terms of climate, soil type, land cover, and biodiversity (WWF-Colombia, 2017), and have unique agro-industrial management approaches (Castiblanco et al., 2015) (Henson et al., 2012). Due to the limitations in obtaining complete and recent LUC information, national data (Torres, 2018) and regional data (Castiblanco et al., 2013) were obtained. We assumed that these studies are representative of the type of LUC and carbon stock effects; however, is a degree of uncertainty is present. These studies include the most detailed data available to date (2000–2012). Moreover, our calculations are based on a 30-year plantation lifetime and include both below- and above-ground biomass (oil palm plant, ground cover vegetation, and organic matter). In addition, it is assumed that CO_2 assimilation in the crop occurs in the trunk and in the fronds of the plant; thus the FFBs (CPO, kernel, EFB, fiber, and shell) are regarded as carbon neutral (Wicke et al., 2008).

2.4.1.2. Sensitivity analysis. A sensitivity analysis was undertaken to compare the impact of LUC emissions linked to different values of carbon stock in various land use categories for Colombia.

[4] NPV shows the difference between all income and expenses expressed in current currency and IRR considers the expected future returns on investment. The viability of a project is indicated by NPV equal to or greater than zero. The viability of projects must be considered when the IRR is equal to the discount rate and NPV is zero (Sapag and Sapag, 2008).

[5] Primary data is crucial to assess any situation as it allows reducing the assumptions raised, as well as reducing the uncertainty of the results. However, obtaining the total information of a specific sector of a country is not an easy task. Currently, in Colombia, there are about 65 POM in operation and more than 5,000 oil palm plantations, then collecting information from all of them would be a monumental challenge and would require a large investment in both human and economic resources to achieve it. However, for this study, it was possible to collect the primary information of 70% of the country's FFB processed in 2017 (i.e., 28 POM), which is still representative and allows specific and strategic improvements for the whole sector.

Table 1
Land use converted to oil palm nationwide and in the three oil palm regions (2000–2012).

Land use/Cover	% of land cover converted to oil palm			
	National[a]	Regional[b]		
		North	Central	Eastern
Pastures	45.9	26.0	52.8	68.8
Herbaceous vegetation	19.5	2.4	4.3	1.1
Forests	5.9	3.3	10.9	5.7
Seasonal crops	23.7	4.1	0.2	11.7
Perennial crops	1.4	40.6	6.4	4.3
Heterogeneous agricultural areas	-	23.6	20.0	5.5
Other land covers[c]	3.6	0.0	5.3	3.0

[a] Adapted from (Torres, 2018), who studied official data (i.e. Colombian Institute of Hydrology, Meteorology and Environmental Studies - IDEAM and other government institutions) for the period 2000–2012.
[b] Adapted from (Castiblanco et al., 2013), who presents data from IDEAM, other field data, and satellite data for the period 2002–2008.
[c] This includes urbanized areas, bare soil with sparse vegetation, and water bodies.

Table 2 shows the land use categories that have been converted to oil palm. Each category has three values of carbon stock found in the literature, which was divided into maximum values, minimum values, and a value defined as "*National*", which is a conservative value used to analyze the impact of LUC emissions in the *current situation*.

2.4.1.3. Plantation management in the current situation. Inputs such as agrochemicals, water, and electricity are included. The nursery stage is not included. Chemical fertilizer application and fuel consumption are considered (i.e. diesel for FFB transport and gasoline used by supervisors). The crop yield is on average 19.3 t FFB ha^{-1} $year^{-1}$ (for more information see A.1).

2.4.1.4. POM in the current situation. Fibers and shells are used as fuel in the boiler for steam generation, however, CO_2 emissions from biomass burning in the boiler are not considered since the emissions come from a biogenic source. It is considered 30 t FFB h^{-1} as the POM production scale. Palm kernel oil extraction and palm kernel meal are not considered. Table 4 shows the summary data for this stage. We assumed a CH_4 production rate of 0.36 m^3 CH_4 kg^{-1} COD removed (Yacob et al., 2006). The data collected during fieldwork showed that only eight of the 28 surveyed POMs carry out biogas capture and only four of those generate electricity from biogas (more input data in Appendix A.2).

2.4.2. Emissions data in future scenarios

In both future scenarios A and B, the emissions were calculated for a representative study case of the country where the CPO chain is optimized to produce several biobased products. In *future scenario A*, the production of BD,[6] biogas, cogeneration, and compost are analyzed. While in *future scenario B*, the production of BD, biogas, cogeneration, and pellets are analyzed.

2.4.2.1. LUC in the future scenarios. The future emissions generated by LUC due to oil palm expansion must be considered to avoid carbon losses through deforestation. Fig. 3 shows a Land Suitability

[6] BD process involves physical refining (refined, blanched, and deodorized); transesterification; esterification of the free fatty acid (FFA); BD purification; glycerin purification (USP), and methanol recovery.

Table 2
Carbon-stock values in land use-categories for Colombia.

Land use-categories	t C ha^{-1}		
	National[a]	Min.	Max.
Forest	147.5	48.1[a]	211[c]
Herbaceous vegetation	14.1	14.1[a]	113[c]
Pastures	6.4	6.4[a]	7.4[b]
Seasonal crops	4.2	4.2[a]	33.1[c]
Perennial crops	28.9	28.9[a]	28.9[a]
Heterogeneous agricultural areas	5.8	5.8[a]	5.8[a]
Other land covers (bare soil, sparse vegetation, and water bodies)	0	0[b]	16.4[b]
Oil palm plantations	113[d]	113[d]	129[c]

[a] Data from (Yepes et al., 2011). Carbon-stock value only includes above-ground biomass. Due to the uncertainty in the estimations of GHG emissions associated with the LUC, the IDEAM undertook an estimation of carbon emissions from forest conversion in the country. In addition, reference values for some land uses that are used in this study were designated as "National".
[b] Data from (Henson et al., 2012).
[c] Data from (Castanheira et al., 2014).
[d] Data from (Rivera-Méndez et al., 2017). Carbon-stock value includes palm tree (trunk, fronds, roots), cover vegetation and associated organic matter.

Map[7] for the establishment of oil palm crops in Colombia, as well as the extent of current palm oil plantations (purple areas). In addition, this figure shows the potential new areas for oil palm expansion cover approximately 23 Mha centered in the eastern, central, and northern regions of the country. The dark green areas on the map represent those areas with high potential (5.2 Mha), while light green areas represent moderate potential (10.9 Mha) (UPRA, 2018). The most favorable areas for oil palm expansion are agricultural areas (crops) and livestock areas (pasture areas) (UPRA, 2016) (Castiblanco et al., 2013). It means that indirect LUC must be avoided by the use of suitable land for oil palm and better agricultural efficiencies through the increase of the yields of crops and livestock production (Wicke et al., 2012) (Gerssen-Gondelach et al., 2017). Table 3 shows the LUC and carbon stock for both future scenarios A and B. Note that for future scenario A and B, the same LUC and carbon stock conditions apply. As mentioned before, the only difference between future scenarios A and B is the use of EFB for the production of pellets or the production of compost.

Table 4 shows the primary input data for future scenarios A and B. In addition, it shows a comparison between the data for future scenarios vs. the *current situation*. The transport by trucks from the mill to the BD plant is not considered in the future scenarios since the industrial[8] zone is assumed to be located in the same area. The treated POME is used for irrigation in the nearest plantation to reduce clean water consumption. In the cogeneration stage, steam from the biomass boiler[9] is directed to a backpressure turbine[10] to generate electricity. The surplus steam from the steam turbine is used as saturated steam in the POM and BD plant to supply heat. A low heating value (LHV) of 13.8 MJ kg^{-1} biomass is considered. In addition, a value of 140.6 kWh kg^{-1} steam is considered (Husain et al., 2003). A biogas engine generator is also used to generate electricity (2.2 kWh/m^3 biogas). Air emissions from biogas and power generation are taken into account. Compost application (at a rate of 10% chemical fertilizer application rate) was considered in *future scenario A*.

2.5. Economic assessment data

The FFB production costs are calculated by dividing the total annual cost of one ha of oil palm (includes establishment and maintenance costs) by the volume of FFB produced per ha. For the POMs and BD plants, the production costs of the primary product (CPO or BD, respectively) are calculated by dividing the total annual costs by the volume of product produced per year. Table 5 shows the key parameters to calculate the costs of the CPO production chain. The CAPEX is calculated based on collected data costs or as provided by experts. In the mill, the CAPEX is obtained by multiplying the cost per installed unit (mill production capacity) by the final number of units installed (t FFB h^{-1}). Therefore, CAPEX depends on the scale of the mill and is 30 t FFB h^{-1} in the *current situation* and 70 t FFB h^{-1} in both *future scenarios A and B*.

3. Results

3.1. GHG emissions in the current situation

Fig. 4 shows the average mass and energy flows of the 28 POMs. The results are expressed in 1 t CPO. In the CPO extraction process, 78% of the fiber and 96% of the shells are used to produce steam and electricity. To run the mill, about 103 kWh of electricity is required; 10% of the electricity came from a biogas engine, 30% from the

[7] Land Suitability Map (scale 1:100.000) was developed by *Rural Agricultural Planning Unit of Colombia* (UPRA, 2016) as a national tool for planning efficient land use for sustainable and competitive development. To develop the map, UPRA used multicriteria analysis of physical, environmental, and socioeconomic components weighted according to the characteristics of the palm oil production chain for each area. The map allows for the identification of the geographic areas that present appropriate conditions for the establishment and development of the oil palm. It is highlighted that:

- Unsuitable means areas in which the development of oil palm crops is not feasible due to physical or environmental conditions.
- No development is permitted in areas with legal restrictions.
- Collective territories require a different approach in order to protect the cultural heritage and the right to self-determination of these communities.
- Oil palm crops will not jeopardize natural areas or provision of ecosystem services (i.e. forests, moorland, water bodies, aquifer recharge zones) (UPRA, 2016).

[8] The industrial zone, in future scenario A, includes the area where the POM, BD plant, cogeneration area, and compost production plant are located. The industrial zone, in future scenario B, includes the area where the POM, BD plant, cogeneration area, and pellet production plant are located.

[9] Boiler conditions: efficiency 79%, 370 °C, and 36 bar.

[10] In Colombia, the backpressure turbine is traditionally used to produce electricity in the POMs, where steam is generated by biomass combustion in a boiler. Then, the residual steam from the turbine is sent to the mill process. In the backpressure turbine, the inlet pressure ranges from 20 to 24 bar and produces up to 50,000 pounds of steam per hour. The turbine steam outlet is about 8–10 bar. According to (Arrieta et al., 2007), in a POM, the heat rate is 14–60 MJ kWh^{-1}, and depending on the boiler size, the power generated by this system can reach an installed capacity of 1,200 kW with an installation cost of around USD $690-850 kW^{-1}.

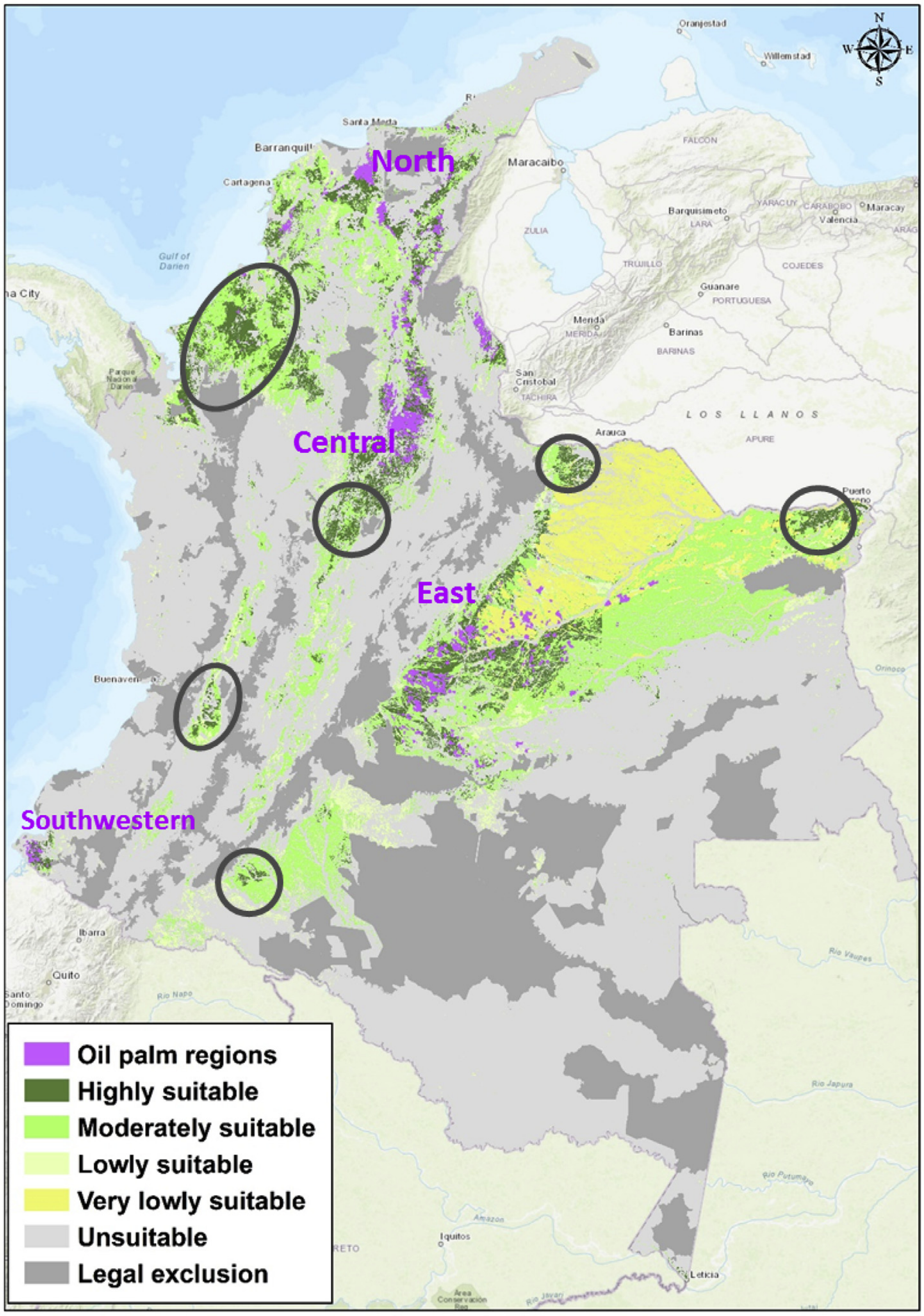


Fig. 3. Land suitability map for oil palm crops in Colombia vs current oil palm regions (adapted from UPRA, 2018). Colombia has 114 Mha of which 74 Mha have restrictions for their use (i.e. natural forests, moor areas, riparian buffer zones, water bodies, wetlands, natural parks, urban areas, and cultural protection areas). Which means there are 40 Mha available for agricultural development nationwide (food, feed, livestock and biomass production). This availability is conditioned to low, moderate and high levels of suitability for its use. In addition, of the 40 Mha available, only 7.6 Mha are currently being used nationwide (UPRA, 2018). In 2018, the area planted with oil palm in Colombia was 0.54 Mha (purple areas), of which 41% are sown in the eastern region, 31% in the central region, 24% in the northern region, and 4% in the southwestern region of the country (Fedepalma, 2019). The black circles show some interesting potential new areas for oil palm expansion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

steam turbine, 13% from an electric generator (diesel), and 47% from the national grid. It can be seen that 68% of biogas is released into the atmosphere (i.e. more than 70% of the mills did not have biogas capture at the time of this study). No specific use for the EFBs was reported according to the survey conducted. Although some mills used EFB as a soil conditioner, it was reported that in most cases this practice is not feasible as the transport of EFB over long-distances is expensive. Consequently, EFBs were commonly sent to the closest landfill, which contributes to additional CH_4 emissions.

The GHG emissions along the CPO production chain, in the *current situation*, are shown in Fig. 5. The average carbon footprint is -689.8 kg CO_2eq t^{-1} CPO, where LUC, POME (CH_4), and chemical fertilization are the primary factors contributing to GHG emissions. Eight mills have already eliminated CH_4 emissions from POME through biogas capture and subsequent flaring (four of them generated electricity using biogas). The CH_4 emissions ranged between 357.4 and 1,588.4 kg CO_2eq t^{-1} CPO. This wide variation

Table 3
Land-use change and carbon-stock for future scenarios.

Land use/covers	% Land-cover converted to palm oil[a]	Carbon Stock (t C ha^{-1})[b]
Pasture	60	6.4
Herbaceous vegetation	10	14.1
Seasonal crops	5	4.2
Perennial crops	10	28.9
Heterogeneous agricultural areas	15	5.8

For calculations in oil palm plantations, the oil palm carbon stock is 113 t C ha^{-1} (Rivera-Méndez et al., 2017).
[a] Data based on the Land Suitability Map from (UPRA, 2018) where the areas suitable for oil palm cultivation correspond to dark green and light green areas in Fig. 3. The study by (Castiblanco et al., 2013) was also taken into account to identify the future expansion of oil palm in Colombia.
[b] National official data from IDEAM (Yepes et al., 2011).

Table 4
Summary of the key input data for future scenarios A and B in comparison with the current situation.

Variable		Current situation (national average)	Ref.	Future Scenario A and B (max. value from data collected)		Ref.
Mainly product		CPO	*	BD		*
Oil palm plantation management						
LUC		Data from Table 1		Data from Table 3		
Crop Lifetime		30 years	*	30 years		*
Crop yield		19.3 t FFB ha^{-1} $year^{-1}$	*	30 t FFB ha^{-1} $year^{-1}$		*
Nursery stage		Not included		Not included		
Chemical fertilization		Urea Ammonium nitrate	*	Calcium nitrate		*
Organic fertilization/biomass		No	*	Compost application		*
Palm oil mill						
Installed capacity or scale		30 t FFB h^{-1}	*	70 t FFB h^{-1}		*
Oil extraction yield		21.35%	*	22.11%		*
Biogas capture		32.2% for electricity, 67.8% released into the atmosphere	*	100% used as boiler fuel, biogas engine, and flaring		*
Biomass uses	EFB	No specific use	*	Compost (scenario A), pellets (scenario B)		*
	Fiber	Boiler fuel (steam)	*	Boiler fuel for cogeneration		* **
	Shell	Boiler fuel (steam)	*	Boiler fuel for cogeneration		* **
	POME	Chemical oxygen demand (COD) removal, Discharge to water source	*	COD removal, Biogas for steam, compost production, and irrigation		*
	FFA	No	*	Esterification		*
Biomass pretreatment		No	*	Chopped EFBs (**A**), Chopped and dried EFBs (**B**)		* **
Electricity source	National Grid	47%	*	**Scenario A** 0%	**Scenario B** 10.5%	* **
	Diesel	13%	*	0%	0%	* **
	Cogeneration	30%	*	68.6%	89.5%	* **
	Biogas	9%	*	31.5%	0%	* **

* Production data from the data collected during fieldwork.
** Data from BioPB model (Cenipalma).

shows the differences in the efficiency of COD-removal within the POME treatment systems caused by the organic matter content and lagoons system operation (e.g. residence time, presence of bacteria, and the removal of sediment). The survey revealed that the initial COD of the POME ranged from 19,000 to 97,777 ppm (mg l^{-1}) while COD at the point of discharge ranged from 165 to 16,572 ppm. Resolution 631/2015, from the Colombian Ministry of Environment, established permitted levels for pollutant concentrations in wastewater discharge which must be met by the POMs (MADS, 2015). The improvement of efficiency of COD-removal should be considered since in the resolution, the maximum COD threshold allowed is 1,500 ppm at the point of discharge.

Fig. 6 shows the regional contributions to national GHG emissions. The central region had the highest LUC emissions, while the eastern region had the lowest. In the Colombian eastern region, pastures and seasonal croplands were predominately converted for palm oil production, while in the central region, most land conversions affected pastures (52.8%) and forests (10.9%). A large increase in LUC emissions results from the conversion of forest to arable land. The eastern region is characterized as having the largest number of POMs with biogas capture from the lagoons (five mills of the 28 mills surveyed) which contributes to about 35% reductions in CH_4 emissions.

3.1.1. Sensitivity analysis

Table 2 indicates the data used for carbon stock values per land use category, which was used to determine the contribution of LUC emissions. The emissions generated in the rest of the CPO production chain (fertilization, POM, diesel consumption, agrochemicals, and POME) were taken from the calculations of the national

Table 5
Parameters for the economic evaluation of the palm oil chain in Colombia[a].

Discount rate[b]	12%
Equipment lifetime	30 years
Investment expenditure	100% in first year
POM annual load[c]	5381 h (current situation); 6,000 h (future scenarios)
Raw material[d]	
FFB	125 USD_{2017} t^{-1} (current s.); 110 USD_{2017} t^{-1} (future sc.)
CPO	735 USD_{2017} t^{-1} (current s.); 646 USD_{2017} t^{-1} (future sc.)
Operational costs	
Plantation costs	*(% of the total crop costs)*
Crop establishment[e]	4%
Crop maintenance	
Fertilization	29%
Harvesting and FFB transport	25%
Agricultural works, supplies, and machinery	22%
Opportunity cost of land	10%
Management costs	10%
POM costs	*(% of the total POM costs)*
Fixed costs	42%
Labor	28%
Equipment and infrastructure maintenance	16%
Electricity	9%
Management costs	5%
BD plant costs[f]	*(% of the total BD plant costs)*
Feedstock	73%
Supplies	21%
Labor	2%
Quality Analysis	1%
Maintenance	1%
Electricity	2%

[a] Parameters came from data collected during fieldwork and the study by (Mosquera et al., 2018). Costs were converted from Colombian pesos (COP) to US dollars (USD) using the 2017 exchange rate (i.e. COP 2,951/1 USD) (http://www.banrep.gov.co/es/trm).
[b] 8% is the real discount rate used by (Mosquera-Montoya et al., 2017), to which we added the average inflation rate for the period 2010–2017 (4%). This yields the 12% nominal discount rate.
[c] In the *current situation*, it is work hours per year obtained from the median collected data.
[d] It is expected that the raw material prices decrease when production yield increases.
[e] This includes crop infrastructure, sowing of palm oil, and coverages, nursery, and others.
[f] Data was taken from (Acevedo et al., 2015). CPO transport from the mill is not considered since the BD plant is assumed to be located in the same area.

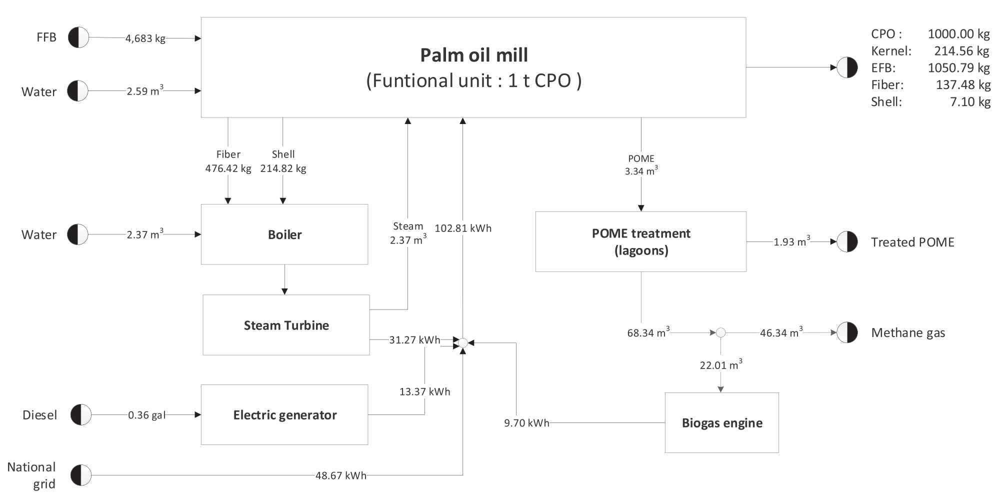


Fig. 4. Mass and energy flows in the current situation (CPO production chain).

average or *current situation*. Fig. 7 shows that the carbon stock value directly influences LUC emissions, contributing 16%–28% of the total emissions. This point to the importance of using specific carbon stock values from areas converted to palm oil. For example, using the maximum and minimum values of carbon stock assumed for oil palm plantations, the LUC emissions ranged from 327 to 695 kg CO_2eq t^{-1} CPO (purple bar), with a carbon stock of −3 to −3.4 t CO_2eq t^{-1} CPO. The negative value indicates a net carbon capture in oil palm plantations.

3.2. GHG emissions in future scenarios

In both future scenarios A and B, it was assumed an increase in crop yield of about 3.5% compared to the *current situation*. Another improvement was the use of all biomass produced during the CPO extraction; also it included biogas capture and BD production. Fig. 8

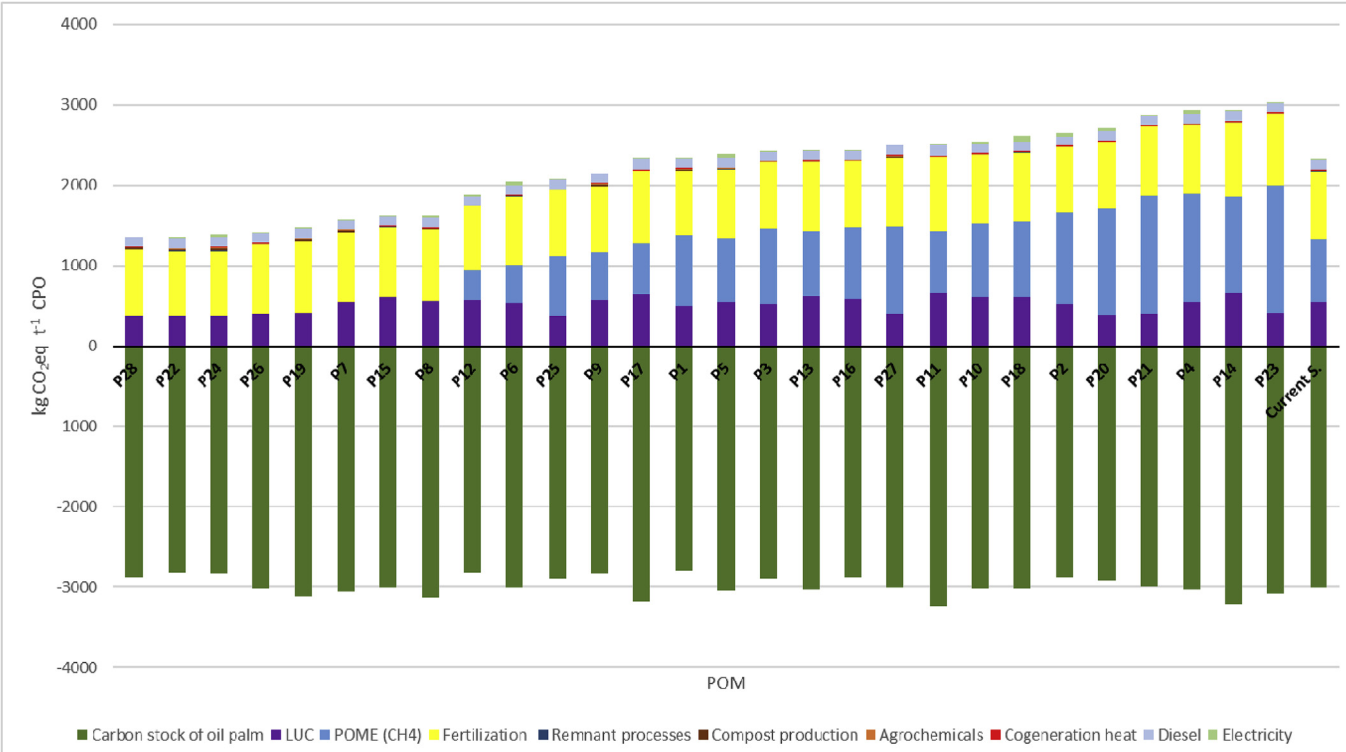


Fig. 5. GHG balance in the current situation and emissions for each surveyed POM (Each mill is represented by the letter P and a number assigned from 1 to 28. The national average GHG emissions are shown in the "current situation" bar).

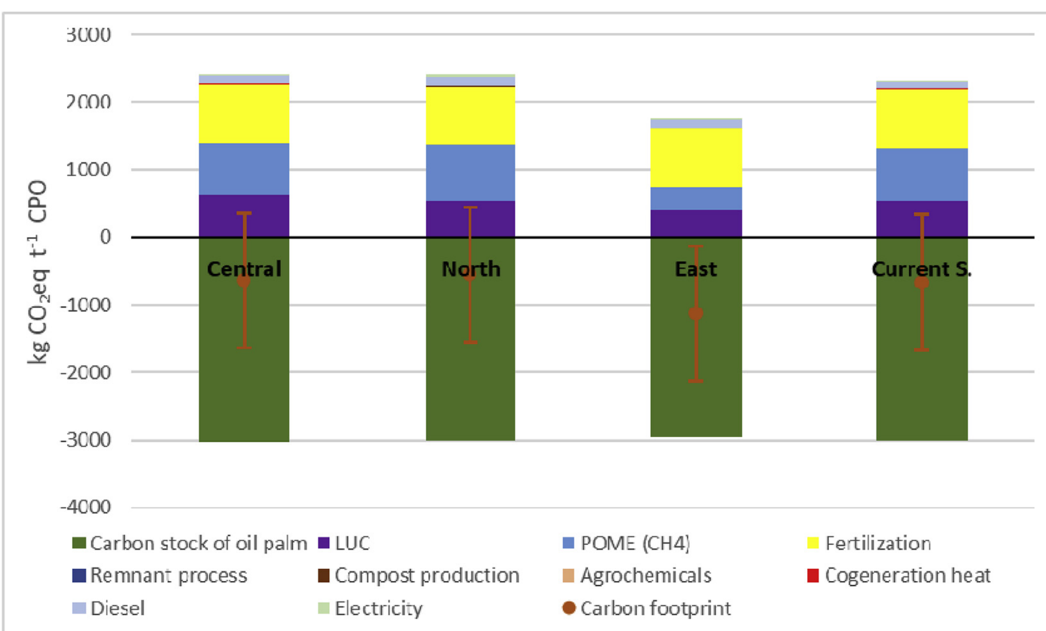


Fig. 6. GHG emissions in each Colombian oil palm region (the orange bar represents the median, max., and min. carbon footprint data). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

and Fig. 9 show the overall mass and energy flows for both future scenarios A and B. The results are expressed per 1 t CPO. In *future scenario A*, the fiber, shells, and biogas were used to produce steam (4,095 kg t^{-1} CPO) and electricity (335 kWh t^{-1} CPO) to meet the demand of the whole system, with an electricity surplus of 115 kWh t^{-1} CPO, which can be sold to the national grid.[11] The EFBs were

[11] More information about the conditions of sale of surplus electricity to the national grid can be found in the Colombian Resolution 030/2018 (CREG, 2018).

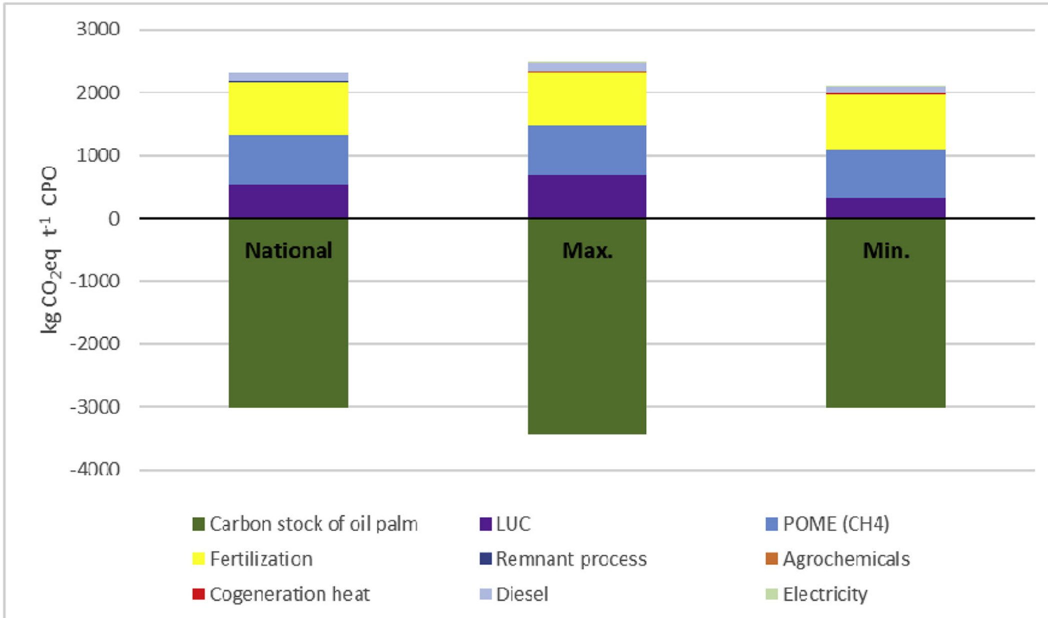


Fig. 7. Impact of LUC on the GHG emissions in the production of CPO (sensitivity analysis).

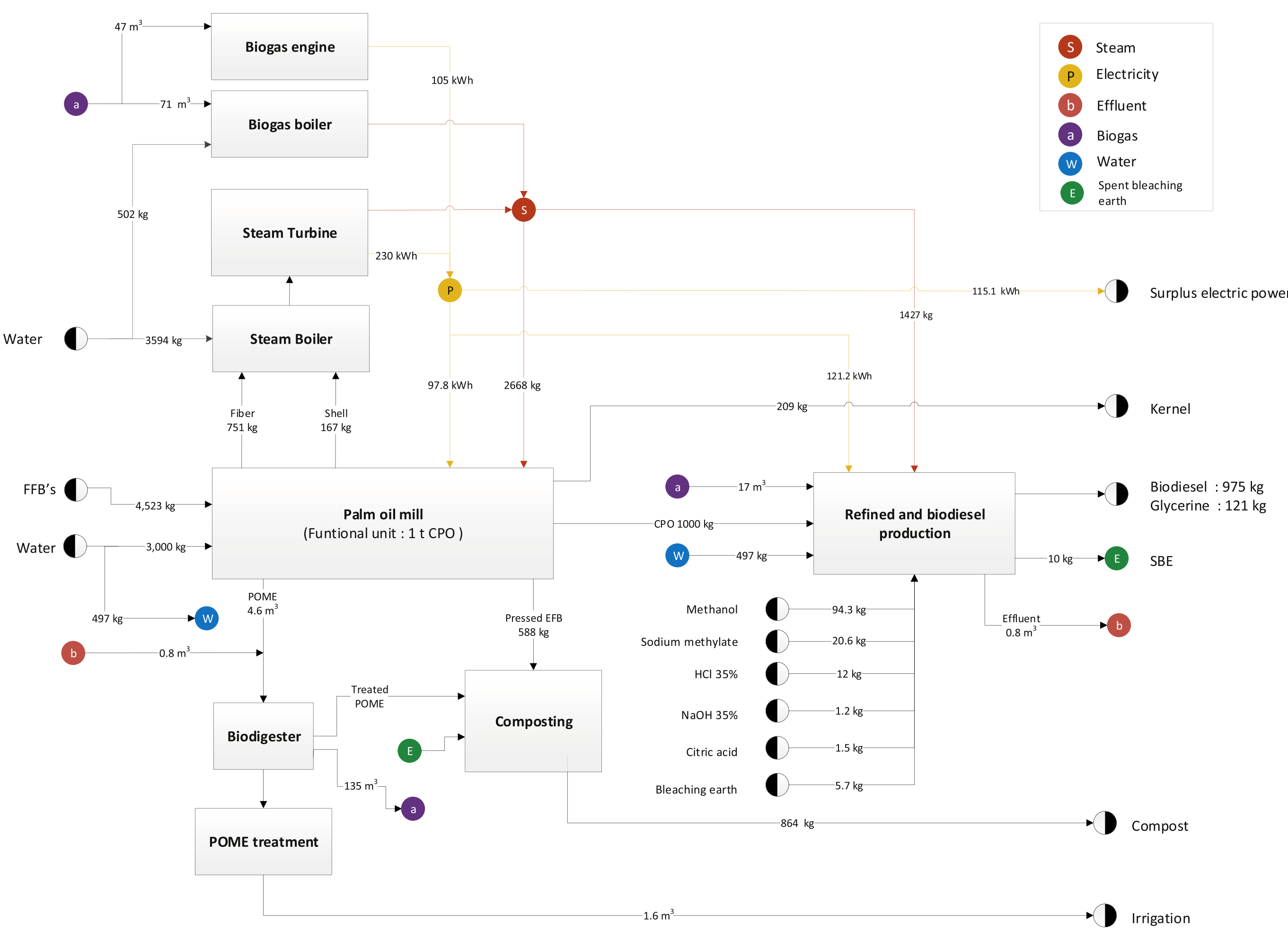


Fig. 8. Mass and energy flows in future scenario A with compost production.

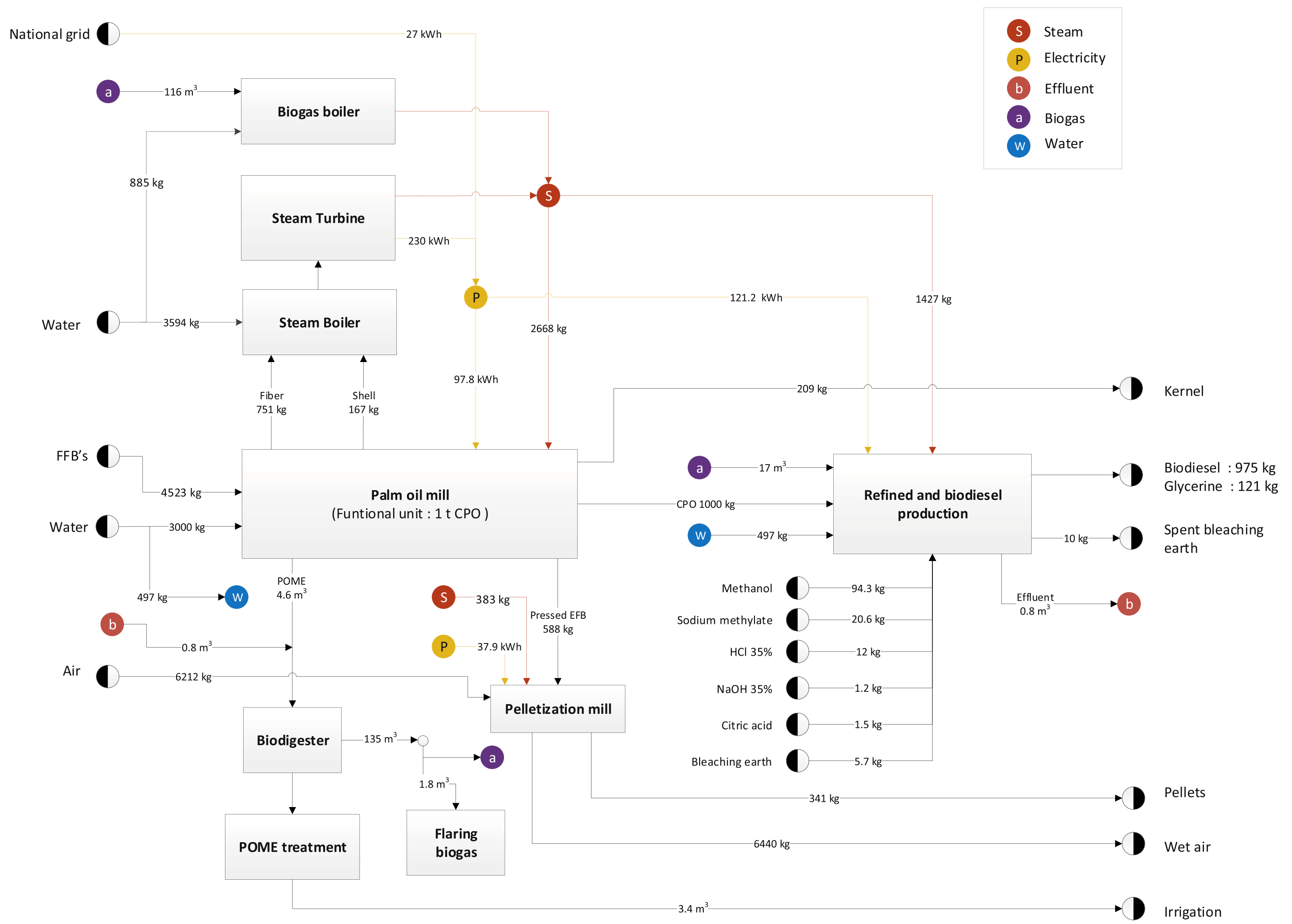


Fig. 9. Mass and energy flows in future scenario B with pellet production.

pre-treated through pressing and chopping, and composted with the treated POME and the spent bleaching earth (SBE) from the CPO refining process. The compost was used in the field as an organic fertilizer, applied at a rate of up to 10% of that of chemical fertilization. In *future scenario B* (Fig. 9), the pelletizing process requires a greater volume of steam to dry the biomass by 10%; and 86% of the biogas produced was used for producing steam in the boiler. As such, it is not possible to generate electricity with biogas. Therefore, in *future scenario B*, 27 kWh t^{-1} CPO of electricity must be purchased from the national grid in order to supply electricity for the process. In *future scenario B*, the volume of biogas required to generate electricity with a turbine (140 m^3 t^{-1} CPO) is greater than the volume of available biogas (118 m^3 t^{-1} CPO). Therefore, it is not possible to obtain an electricity surplus under the *future scenario B* conditions.

The GHG emissions along the CPO production chain in future scenarios A and B are shown in Table 6, along with GHG emissions from the *current situation*. Note that due to improvements made in the CPO production chain, total emissions in *future scenarios A and B* are lower than in the *current situation* as there are no CH_4 emissions and LUC emissions are reduced. Methane capture is a practice that reduces emissions immediately and generates an economic benefit to the POM since biogas can be used for power or heat generation, thus reducing the consumption of fossil fuels. Thereupon for future scenarios, crop fertilization will be the primary factor contributing to the emissions since oil palm crops have a high nutrient demand (Galindo and Romero, 2012). Fertilization emissions in *future scenario A* included compost application emissions (3.7 kg CO_2eq t^{-1} CPO), where each kilogram of compost replaced only 0.1 kg of chemical fertilizer. Notice that compost cannot be used as a total replacement or radical substitution for chemical fertilization because the release of nutrients from compost is a slow process and the oil palm crop requires high levels of available nutrients (Galindo and Romero, 2012).

When analyzing the system boundary until the biodiesel production plant, Table 7 shows that the carbon footprint of *future scenario A* is slightly greater (−679.6 kg CO2eq t-1 BD), than the carbon footprint of *future scenario B* (−771.2 kg CO2eq t-1 BD), mainly because fertilization emissions are higher in *scenario A*. For both future scenarios A and B, about 13% of emissions are due to LUC, about 68% is due to fertilization and agrochemicals, and about 11% corresponds to the process of refining-transesterification. When comparing these results with the results of the emissions in the study by Yáñez et al. (2011), which was a study that used information from the five BD producing companies in Colombia in 2010, it is observed that the greatest differences in the emissions come from the fertilization, POME (CH_4), diesel consumption and steam production. POME methane emissions are non-existent in *future scenarios A and B* of this study since the capture of biogas was assumed for power generation. In addition, emissions from diesel consumption are less in both future scenarios of this study due to it was not included the CPO transport because the mill and the BD

Table 6
Comparison in GHG emissions and carbon footprint in the CPO production chain for analyzed scenarios (kg CO_2eq t^{-1} CPO).

Source	Current situation	Scenario A	Scenario B
Carbon Stock			
Oil palm crop	−3,014.1	−1,852.3	−1,852.3
Emissions			
LUC	537.6	151.1	151.1
POME (CH_4)	778.7	0.0	0.0
Fertilization	860.5	807.1	741.0
Compost production	0.0	3.7	0.0
Diesel	114.7	54.8	54.7
Cogeneration (power)	14.7	0.4	0.5
Cogeneration (heat)	9.1	7.6	7.6
Agrochemicals	6.3	4.3	4.3
Remnant processes	2.6	1.7	1.6
Total emissions	2,324.3	1,030.6	960.8
Balance			
Carbon footprint	−689.8	−821.7	−891.5

- Note that in this table the system boundary for the GHG balance is CPO production for all the cases.
- Remnant processes contribute less than 1% to total GHG emissions.
- **Carbon stock** in oil palm crop includes the palm tree (fronds, trunk, and roots), cover vegetation, and associated organic matter. This value was estimated dividing by 30 years of plantation lifetime, and by the average yield of the plantation (t FFB ha^{-1}). The carbon stock variation, between the scenarios, is due to the crop yield assigned to each of them, which is 19.3 t FFB ha^{-1} $year^{-1}$ in the *current situation* and 30 t FFB ha^{-1} $year^{-1}$ for both *future scenarios* (see Table 4).
- The emission/removal ratio in carbon stock in palm oil crop for the *current situation* is 0.74 (i.e. for each kg of CO_2 that is being absorbed; 0.74 kg CO_2 is emitted). For *scenario A*, it is 0.54 and for *scenario B*, it is 0.50, which means that less CO_2 is emitted in both future scenarios. Note that in *scenario A*, compost production generates emissions by its production and emissions by its application on the field.
- Fertilizer emissions in the future scenarios will be lower than in the *current situation*; however, in *scenario A*, the emissions are greater than in *scenario B* due to the direct and indirect N_2O emissions caused by compost application.
- Compost emissions (CH_4 and N_2O) originate from the degradation of biomass.
- Diesel emissions correspond to the diesel consumption in FFB transport, trucks and tractors.
- Cogeneration emissions are divided into power (electricity) and heat (steam). Electricity emissions in the *current situation* correspond to the emissions of the four sources (diesel, national grid, cogeneration, and biogas), whereas electricity emissions in the future scenarios account only for biogas and cogeneration (biomass). Biogenic CO_2 emissions of the biomass were not considered. Note that the difference in heat between the *current situation* and in the future scenarios is due to increased steam consumption in the BD plant.
- Pellets production emissions are approximately 0.6%, which are included in the emissions by cogeneration (power and heat).

plant are located in the same area.

3.3. Net energy ratio

Fig. 10 shows a comparative analysis of NER for each scenario. In all cases, the crop stage had the highest fossil energy consumption (2.8–6.7 GJ t^{-1} BD). In the *current situation*, the NER is 2.2 MJ renewable MJ^{-1} fossil (Comparison1, C1 yellow line), where only fiber and shell are included as renewable energy sources. In contrast, the NER increases to 8.5 MJ renewable MJ^{-1} fossil (C8 yellow line) by adding CPO and all byproduct energy. In the *future scenarios A and B* (BD chain), the NER is greater than in the *current situation* (CPO chain), due to the increase in renewable energy from the primary products. For instance, in *future scenario A* for each unit of fossil energy required to produce BD and compost, 13.72 units of available renewable energy is obtained (C1 green line).

3.4. Economic performance assessment

3.4.1. Current situation

In the *current situation*, the CAPEX is estimated at 37.8 USD t^{-1} CPO (51% POM costs and 49% crop costs). The OPEX is estimated at 519.2 USD t^{-1} CPO (86% crop production costs and 14% POM costs) (Fig. 11a). The processed FFB processed has an estimated value of 125 USD t^{-1} FFB. The NPV is estimated at 895 USD t^{-1} CPO and project profitability[12] shows 34% IRR. To quantify possible costs of breaches of environmental law, we assumed the mill was noncompliant with maximum permissible levels of contaminants in discharge, and the mill was closed for one week. As a result, the cost of that closure week is 3.6 USD t^{-1} CPO, which corresponds to the value of FFB processing in another mill. This could also imply other disadvantages, such as extra expenses for FFB transport over long distances and a reduction in the CPO selling cost with a poorer quality product below specifications (such as free fatty acid content, peroxides, and humidity). Fig. 11a shows that CPO production costs are cheaper in *future scenarios A and B* than in the *current situation*. This due to the higher yield of the crop, the larger scale, and cheaper feedstock (FFB) at the mill. The estimated income of approximately 800 USD t^{-1} CPO is based on the expected sale of CPO (92%), power surplus (5%), and pellets (2%).

3.4.2. Future scenarios A and B

The CAPEX and OPEX are quite similar in both *future scenario A* and *future scenario B*. The CAPEX is estimated at approximately 49 USD t^{-1} BD (crop 32%, POM 29%, biogas/cogeneration 8%, BD plant 30%, and composting or pellets 1%). The OPEX is estimated at approximately 680 USD t^{-1} BD (crop 55%, POM 8%, biogas/cogeneration 2%, BD plant 34%, and composting or pellets approximately 1%). In *future scenarios A and B*, the NPV is estimated between 1,825 and 2,178 USD t^{-1}BD and the profitability of the project showed an IRR from 38 to 43%. An estimated income of approximately 1,075 USD t^{-1} BD is expected based on expected sales of BD (95%), power surplus sale (4%), and pellet sales (1%). Fig. 11b shows that the BD production chain can be cheaper in *future scenarios A and B* across all stages of the production chain (crop, mill, and BD plant). Fig. 11b also shows the prices of BD and diesel in Colombia. Since 2008, palm oil BD has been mixed with diesel for vehicular use, to reduce reliance on fossil fuels. However, due to the higher production costs of BD, the price of this biofuel is higher than the price of diesel. For instance, in Colombia, the historical price of BD has been around 30 USD GJ^{-1} while in 2017; the diesel price was approximately 10 USD GJ^{-1}. The diesel price per barrel was 54 USD/bbl and the average operating cost for oil production was 16.3 USD/bbl (extraction costs 47% and transportation costs 53%) (Hernandez et al., 2018b). The additional refining cost is estimated at approximately 30% more than crude oil. The oil price fluctuates over the medium and long term (van Vliet et al., 2009). Oil price projections could vary between 30USD and 119USD bbl^{-1} (2020–2030) (van Vliet et al., 2009) (Hernandez et al., 2018a). Considering the need to reduce environmental pollution, the national government has provided some incentives[13] for the production of BD, but in future, further assistance will be

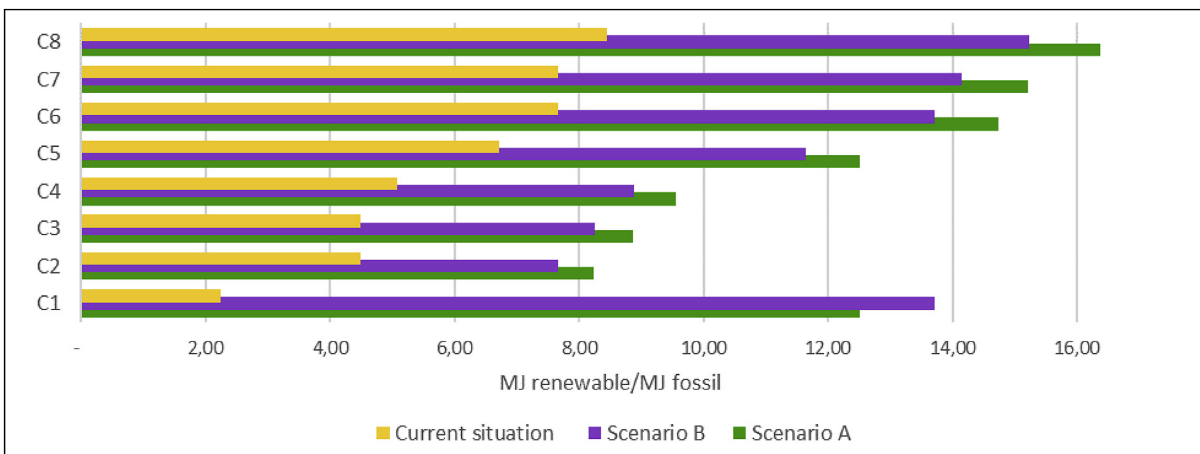
[12] Note that companies must meet national, regional, and local regulations in order to operate within Colombian territory; including environmental regulations otherwise, those companies may face temporary or permanent closure.

[13] Elimination of taxes for machinery and equipment purchase, reduction of income tax for companies in free zones, elimination of National Tax on gasoline and diesel (Law 939/2004). In addition, other benefits such as 1) reduction in logistics costs due to the availability of biofuel locally, compared to the costs of importing diesel. 2) Benefits associated with the costs avoided by the non-use of lubricity improving additives for low and ultra-low sulfur diesel. 3) Benefits for the reduction of costs associated with premature mortality (mainly children and older adults) and morbidity (chronic respiratory diseases), generated by the reduction in toxicity of particulate matter emissions (PM10/PM2.5). 4) Benefits for the populations in the rural areas where the oil palm is cultivated (formal employment) (Torres, 2014).

Table 7
GHG balance in several studies of the Colombian palm oil sector.

Process	The present study					Recent studies for the oil palm sector[a]			
	Current situation	*Future scenario A*	*Future scenario B*	*Future scenario A*	*Future scenario B*	Study 1	Study 2	Study 3	Study 4
Study area	28 POMs	A representative study case		A representative study case		Five BD plants	11 scenarios	Hypothetical POM	A specific plantation
Unit[b]	**kg CO_2eq t^{-1} CPO**			**kg CO_2eq t^{-1} BD**		**kg CO_2eq t^{-1} BD**	**kg CO_2eq t^{-1} CPO**	**kg CO_2eq t^{-1} CPO**	**kg CO_2eq t^{-1} CPO**
Carbon Stock									
Palm oil crop	−3,014.1	−1,852.3	−1,852.3	−1,883.9	−1,883.9	−6,080.8	−894	−5,372.6	−3,388.3
Emissions									
LUC	537.6	151.1	151.1	153.6	153.6	34.4	343	49.1	74.9
Fertilization	860.5	807.1	741.0	820.9	753.7	450.5	61	224.2	351
Agrochemicals	6.3	4.3	4.3	4.4	4.3	5.3	.	6.6	.
POME (CH_4)	778.7	0.0	0.0	0.0	0.0	945.6	179	1689.5	778.7[e]
Compost prod.	.	3.7	.	3.7	.	.	.	.	.
Steam produced	.	.	.	.	.	332.4	.	879.8	.
Diesel	114.7	54.8	54.7	55.7	55.6	468.6	255	79.6	79.6
Electricity	14.7	0.4	0.5	23.8	2.3	56.6	.	60.8	.
Cogeneration	9.1	7.6	7.6	10.9	10.9	.	.	355.7	.
RBD + BD[c]	.	.	.	130.7	130.7	40.3	.	.	.
Remnant proc.[d]	2.6	1.7	1.6	0.6	1.6	374.2	.	0.2	46.8
Total emissions	2,324.3	1,030.6	960.8	1,204.3	1,112.7	2,707.9	838	3,345.5	1,331.0
Balance									
Carbon Footprint	−689.8	−821.7	−891.5	−679.6	−771.2	−3,372.9	−56	−2,027.1	−2,057.3

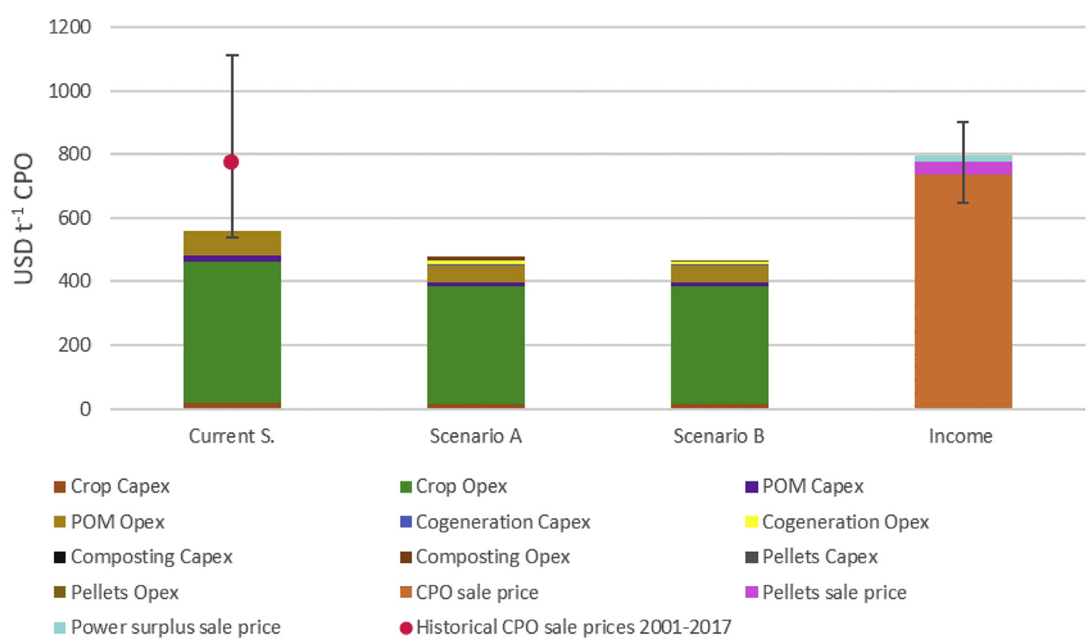
[a] **Study 1** data taken from (Yáñez et al., 2011); **Study 2** data based on (Henson et al., 2012); **Study 3** data based on (Garcia-Nunez et al., 2016); **Study 4** data based on (Rivera-Méndez et al., 2017). Note to compare the GHG emissions in this table, the results from the studies by (Garcia-Nunez et al., 2016) and (Rivera-Méndez et al., 2017) have been expressed per tons of CPO (i.e. 4.68 t FFB t-1 CPO was used for the calculations).
[b] Unit: CPO = Crude Palm Oil; BD = Biodiesel.
[c] RBD + BD process includes the inputs of the refining and transesterification processes (methanol, sodium methylate, citric acid, hydrochloric acid, and SBE).
[d] Remnant processes are those which contribute less than 1% to total GHG emissions.
[e] Data assumed from the *current situation* to add the highest emission from the mill.



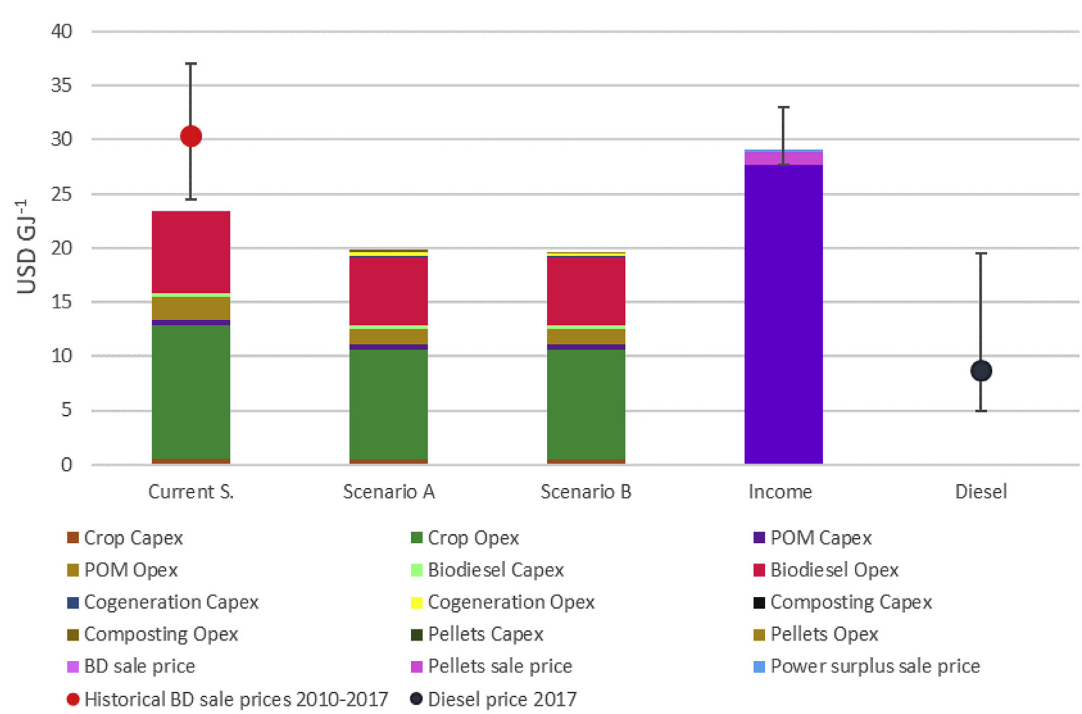
C1*	Shell + fiber (*current situation*)	BD + biogas + shell + fiber (*future scenario A*)	BD + biogas + shell + fiber + pellets (*future scenario B*)
C2	CPO	BD	
C3	CPO (no biogas in this situation)	BD + biogas	
C4	CPO + shell	BD + biogas + shell	
C5	CPO + shell + fiber	BD + biogas + shell + fiber **	
C6	CPO + shell + fiber + pellets	BD + biogas + shell + fiber + pellets ***	
C7	CPO + shell + fiber + pellets (no glycerin)	BD + biogas + shell + fiber + pellets + glycerin	
C8	CPO + shell + fiber + pellets + kernel	BD + biogas + shell + fiber + pellets + glycerin + kernel	

* Comparison1 = C1, corresponds to NER values for the scenarios in the present study (*current situation*, *future scenario A*, and *future scenario B*). This value only includes products that function as renewable energy fuels.
** Future scenario A (pressed EFB are used for compost production and are not included as renewable energy)
*** *Future scenario B* (pellets are produced from pressed EFB).

Fig. 10. NER comparative analysis for the current situation and for future scenarios A and B.



a) Costs analysis in the CPO production chain (CAPEX, OPEX, and Income)



b) Costs analysis in the BD production chain (CAPEX, OPEX, and Income)

Fig. 11. Cost comparison of the current situation and future scenarios A and B for CPO production (top graphic a) and biodiesel production (bottom graphic b).

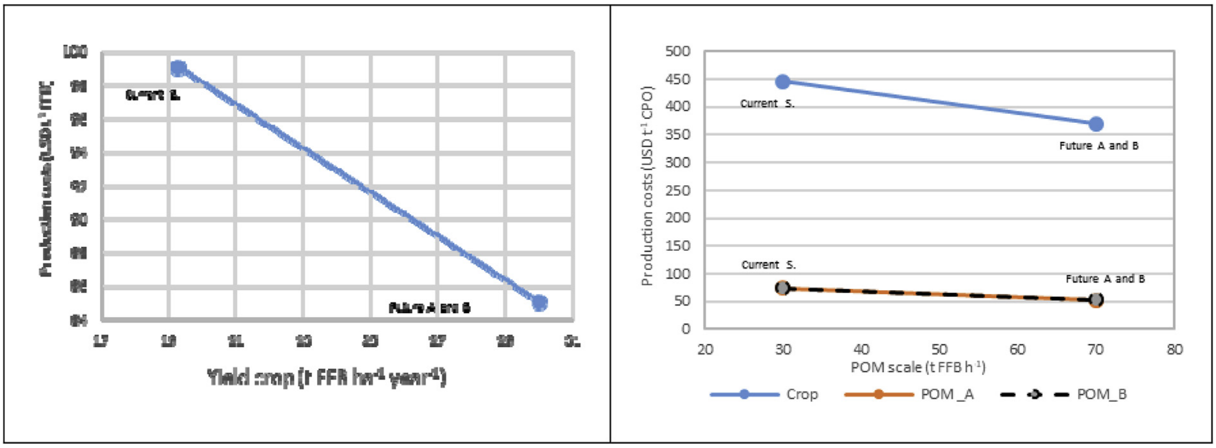


Fig. 12. Production costs in relation to crop yield (left graph) and to the scale of palm oil mill (right graph).

required to reduce BD costs. Fig. 12 shows the sensitivity of CPO production costs to scale applied to all scenarios. The crop yield increase (left) reduces the FFB production costs by 55% when proceeding from the *current situation* to *future scenarios*: the increase in the production scale at the POM (right) reduces the production costs by approximately 25% from the *current situation* to the *future scenarios*.

4. Discussion

Table 7 shows a comparison of some recent **GHG balance** studies for Colombian palm oil, including the present study. Note that the GHG balance varies according to the assumptions made (e.g., data source, data representativeness, parameters included). Despite this, when comparing the carbon footprint reported for Colombia with the most recent analysis reported for Indonesia (0.7 and 26 t CO_2eq t^{-1} CPO (Lam et al., 2019)), the range of the carbon footprint for CPO production in Colombia remains much lower than for Indonesia. Worldwide in the CPO production, LUC, CH_4 emissions, and chemical fertilization have been the major contributors to GHG emissions (Wicke et al., 2008) (Yáñez et al., 2011) (Henson et al., 2012) (Castanheira et al., 2014) (Garcia-Nunez et al., 2016) (Lam et al., 2019).

As **LUC** strongly affects GHG balance (Wicke et al., 2008), the future expansion of palm oil crops in Colombia should be carried out in agricultural areas and livestock areas, with low carbon stock, to prevent deforestation and reduce LUC emissions (Castiblanco et al., 2013) (Pirker et al., 2016). Is highlighted that several studies have shown the deforestation of the forests in Colombia due to palm oil have been much lower than in other producing countries since the expansion has primarily occurred on pastures, herbaceous vegetation, and seasonal croplands (Henson et al., 2012) (Castiblanco et al., 2013) (Castanheira et al., 2014) (Furumo and Aide, 2017). Nevertheless, to prevent deforestation due to the agricultural expansion, strong guidelines, policies, and criteria are required to promote and regulate natural resources and efficient land use suitable for oil palm crops (Castanheira et al., 2014) (Woittiez, 2019) (Khasanah, 2019). Thereby, in the Land Suitability Map restrictions were considered to oil palm crops will not jeopardize natural areas or provision of ecosystem services (UPRA, 2016). A voluntary "Zero Deforestation" agreement was signed between the oil palm sector and the Colombian government, where the sector undertook to eliminate the deforestation footprint of its supply chain (MADS, 2019). In addition, the Colombian government for the proper use of the land is issuing several national laws and policies[14] (MADR, 2018). Besides, a strategy to move towards sustainable and low carbon growth, to protect biodiversity, improving environmental quality and governance, and achieving resilient growth that reduces vulnerability against the risks of natural disasters and climate change (DNP, 2018). On the other hand, since the impact of LUC emissions is linked to carbon stock changes, in Colombia, more precise data and mechanisms to monitor deforestation are required for emissions calculation. It is due to the huge diversity of the Colombian natural forests (from dry forest to tropical humid forest) (IDEAM et al., 2015), where the average carbon stock can vary between 48.1 t C ha^{-1} and 147.5 t C ha^{-1} (above-ground biomass) (Phillips et al., 2011). Then, applying good agricultural practices such as planning the crop location (soil quality, water) and increasing the crop yield will be important to reduce land-use emission (Gerssen-Gondelach et al., 2017), and also to reduce the CPO production costs (Beltrán et al., 2015) (Fontanilla, C;Mosquera, M; Ruiz, E; Beltrán, J; Guerrero, 2015) (Mosquera-Montoya et al., 2017).

CH_4 emissions from the POME treatment system in the *current situation* require great attention, since from the 28 POMs surveyed for this study, only eight mills reported CH_4 capture (biogas). Anaerobic POME treatment produces biogas, which is a mixture of gases where the major component is methane gas (50–70%) (Ohimain and Izah, 2017). Since the global warming potential of CH_4 is greater than that of CO_2 (IPCC, 2013), its capture and management as a renewable source of energy are essential. In the *current situation* of this study, the emissions from the POME treatment correspond to 35% of the total emissions of the CPO production, therefore the significant potential for reducing these emissions when capturing the biogas is considered in a future scenario. Even as analyzed in the *future scenario A and B*, the energy generation with biogas contributes to reducing the environmental impact and increasing the economic benefits of the sector. In addition to the biogas capture, the concept of zero waste at the exit of the POME lagoon system is emphasized to reduce the pollution of water sources (Espinosa et al., 2016), especially when in Colombia the maximum permissible parameters of water pollution are been stronger in recent years (MADS, 2015). For instance, the treated POME can be used for compost production or as irrigation water

[14] For instance, Land use policy (MADS, 2013). Definition of the agricultural frontier (MADR, 2018), among others.

due to its high nutrient content (e.g., nitrogen, potassium, magnesium, and calcium) (Ramirez et al., 2011) (Ohimain and Izah, 2017). The Colombian government has encouraged the use of biomass and biogas for the generation of renewable energy, both to support the internal mill power demand and to the sell surplus electricity to the national grid, through tax incentives that promote the development and use of non-conventional energy sources (MADR, 2016) (Fedepalma, 2017b) (UPME, 2019). In a POM, an increase in biomass utilization efficiency can generate surplus energy for sale, as reported in *future scenario A*, where the use of biomass and biogas met the needs of the process and surplus energy was obtained.

Accordingly, the future CPO production chain must be focus on the emissions reduction to meet international sustainability standards, through the agro-industrial practices optimization that includes i) **increasing crop yield**, the Colombian oil palm sector has worked on the adoption of sustainable agricultural practices and technologies (Cooman, 2018). The aim of those practices is the achieving an increase in the national average yield from 16.2 t FFB ha^{-1} (Fedepalma, 2019) with a palm oil yield of 3.8 t CPO ha^{-1} (Cooman, 2018), to a crop yield around 24 t FFB ha^{-1} with a CPO production of 5 t ha^{-1} by 2023 (Cooman, 2018). However, in the future scenarios of this study, a crop yield of 30 t FFB ha^{-1}, which is equivalent to about 6.6 t CPO ha^{-1} (CPO extraction rate of 22.11%), is proposed. In this context, it is estimated that the oil palm sector of the country must make a great effort to increase the current yields. ii) **Reducing diesel consumption** is mainly focus on the FFB transport stage from the field to the mill, where the use of more efficient vehicles could contribute to reducing emissions. iii) **Adding value to biomass** would contribute to reducing negative environmental impacts and increasing the economic income of the palm sector. Since the biomass residues from the agricultural sector do not require additional land and are not useful for human consumption, it helps avoid deforestation and competition with food production (IEA Bioenergy, 2015). In Colombia, the palm oil sector has the potential for the production of lignocellulosic biomass of approximately one million tons (dry weight basis) with further increases expected but the future uses of biomass depend on its availability and cost (Ramirez et al., 2015). For example, the data collected during the fieldwork showed that most of the EFB did not have a specific use due mainly to the high costs of transport to the field. Consequently, EFBs are disposed of at landfills close to the mill, which has generated problems by the decomposition as leachate, and further CH_4 emissions. Therefore, compost or pellet production and cogeneration (heat and power) are some of the proposals of the future scenarios raised in this study.

The **NER analysis** in the BD production life cycle shows that the fossil energy consumed is lower than the renewable energy produced. The NER values reported in the literature for the BD chain in Brazil and Colombia are between 3.8 and 5.7 (Yáñez Angarita et al., 2009) (de Souza et al., 2010). However, a comparison of the energy balance including all products and byproducts shows that the potential NER value is higher. In an analysis of various biobased products from palm oil, the NER ranges from 17.7 to 22.9 (Garcia-Nunez et al., 2016). In our study, *future scenario B* has a higher NER than *future scenario A* (13.7 and 12.5, respectively). This is due to the production of pellets in *future scenario B* which increases the renewable energy produced, while the production of compost in *future scenario A* consumes a greater amount of fossil fuel. Thus, higher values of NER are observed when the use of biomass as renewable energy is increased (i.e. electricity, pellets, BD).

Regarding **economic performance**, the NPV and IRR are used as indicators of the economic viability of the palm oil sector. These vary according to the CPO market prices. The CAPEX depends on the mill scale and the machinery lifetime. The establishment of a palm oil plantation requires an initial investment and this crop requires a period of vegetative development prior to the beginning of the productive cycle (i.e. third year). Once the palm reaches its mature stage (i.e. year 7), FFB production tends to stabilize and there is income from FFB sales. The costs analysis is directly related to agricultural practices and industrial processing, and yield and costs for each stage in production chain must be optimized (greater profit margin) (Mosquera et al., 2014). Economic benefits and environmental benefits are realized from biomass use and improvements in production conditions, which increase yields in the supply chain. For instance, in the *current situation*, the crop yield was 19.3 t FFB ha^{-1} $year^{-1}$ and the mill processes 5,381 h $year^{-1}$, requiring the planting of 8,400 ha.

However, by increasing the crop yields (30 t FFB ha^{-1} $year^{-1}$) and with a larger processing capacity and time process at the mill (i.e., 70 t FFB h^{-1} and 6,000 h $year^{-1}$), only 14,000 ha of oil palm will be required. This means greater FFB production per year with less land required.

5. Conclusions

This study evaluated the GHG emissions and the economic performance of the Colombian palm oil sector in the *current situation*. Besides, the analysis of two future scenarios, where the GHG emissions can be reduced through the application of good agricultural practices such as a) Reducing LUC impact through planting in suitable and available areas (cropland, pastureland); b) Reducing the use of chemical fertilizers with high carbon footprints (e.g., ammonium nitrate); c) Applying soil conditioners such as compost; d) Increasing crop yield and CPO yield per ha; e) Reducing diesel consumption, and f) Biogas capture. Also, using discharges from the POME system as water irrigation in nearby plantations, whenever possible. Improvements in the CPO production chain in both *future scenarios A and B* allow for a 55% decrease in GHG emissions compared to the *current situation*. In addition, the NER analysis in the BD production life cycle shown a renewable energy gain compared to the fossil energy input at the production system. Note the impact of LUC on total emissions depends not only on the change in land cover but also on the precise allocation of carbon stock values for the converted land cover (LUC mitigation through a sustainable crop yield increase is researched by the authors to an incoming paper).

For all scenarios, the crop operational costs represented the largest investment. However, it is expected that in the long-term scenarios, the total CAPEX and OPEX will decrease by approximately 20% in comparison to the *current situation*. The sale of surplus energy and pellets can contribute around 5–10% of the total income. Future economic evaluations could consider the fact that the investments are going to be staggered over time (e.g., first the planting phase, then the POM establishment and BD plant, etc.). Other scenarios could also be evaluated, such as those in which investors acquire the POM and buy all the FFB from suppliers, or those, which include income from the sale of carbon credits or products with sustainability labels supported by internationally recognized certification systems. The **key** point of this study is that there is significant potential for improvement in GHG balance in the BD production chain. In addition, the economic viability of the BD chain is improved through improving yield, the selection of low carbon stock lands, increased production scale, the production of biogas, pellets, and compost, and cogeneration. The second **key** point is that the sustainability of the palm oil sector requires enforcement of national policies on the use of available land and the prevention of deforestation.

Author contribution statement

Term	Definition
Conceptualization	This publication is part of a PhD thesis at the University of Groningen - the Netherlands. Therefore, the schedule and all the details which include goals and aims were proposed in the TSP (training and supervision plan) approved by the Graduate School of Science.
Methodology	The methodology included the analysis of an agribusiness sector in Colombia, using globally recognized sustainability indicators. The calculations of the indicators were carried out in Excel, the BioPB model and the SimaPro software.
Software	Not applicable
Validation	Each of the co-authors actively participated in the development of the project, in the review and analysis of results. However, the participation of Dr. Mosquera-Montoya in the development/analysis of economic indicators is highlighted.
Formal analysis	Descriptive statistic. Primary data collected using on-site surveys
Investigation	Primary data collected using on-site surveys
Resources	Not applicable
Data Curation	The information collected from the surveys was directly filled in Excel (the original files are kept). Everything is kept updated in the cloud.
Writing - Original Draft	The paper was written indirectly in English. Prior to uploading the paper to the Journal, a language editing at the Elsevier service was made.
Writing - Review & Editing	During each stage of the project development, feedback from the co-authors was received. Even during the adjustment to the comments of the reviewers.
Visualization	All co-authors participated in the data presentation
Supervision	Dr. Professor Andre Faaij had the leadership responsibility for research activity planning and execution.
Project administration	Dr. Professor Andre Faaij was responsible for managing and coordinating the planning of research activities. The PhD student Nidia Ramírez carried out the research.
Funding acquisition	Dr. Professor Andre Faaij was responsible for the acquisition of the financial support for the project leading to this publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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